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Development of plateau dunes controlled by iron pan formation and changes in land use and climate

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ABSTRACT

Plateau dunes are unique landforms which formed as erosion relicts in blow-out areas in Late Pleistocene sandy deposits. They are negative forms in contrast to normal dunes where sand is accumulated (positive form). Plateau dunes are located in the European Aeolian Sand Belt in the Netherlands, Germany and Denmark and they are flat-topped features with a bog in the central part often covered by a thin aeolian sand layer. A conceptual model of formation and further development of plateau dunes in time are presented in detail, using ^{14}C dates of buried peat layers and OSL dates of sandy sediments. Special focus is on the influence of climate factors, pedology, and human activity on the formation of plateau dunes.

1. Introduction

Many landscapes in Denmark are shaped by the wind, e.g. the coastal dune landscape along the west coast and large areas of shifting sand further inland. Inland dunes are generally much older than the coastal dunes and shaped during periods of sparse vegetation. The oldest inland dunes and aeolian cover sands are from the Late Weichselian or Early Holocene. Later in the Stone and Bronze Ages and especially the Iron Age, aeolian landscapes also developed when cultivation and removal of vegetation covers had opened up the landscape (Rasmussen, 2005; Rasmussen and Bradshaw, 2005). In historical times, Denmark deforested during the Little Ice Age in 1250–1850, and in the 17th century, forests covered < 1% of the country. Several villages were abandoned as they were invaded by large inland dunes. Some appear as orderly parabolic or sickle-shaped dunes; others as slightly undulating cover sands. The source of the dune sand is neighboring areas in which deflation surfaces formed. These surfaces now remained coarse sandy or gravelly as the wind has not been able to transport such grain sizes. On very few of these surfaces, erosion remnants of the original landscape appear as low flat "islands" rising over the deflation plain. These are termed the plateau dunes (Fig. 1).

Plateau dunes are characterized by their genesis and shape. They are genetically erosion relics forming "islands" in a rather flat deflation landscape. They can be taller than 4 m and bordered by steep slopes. The top part of the bigger plateau dunes is rather flat with a low sandy rim and a shallow wet central depression; occasionally a free perched water table is present. The natural vegetation mirrors the wetness with grasses and common heather (*Calluna vulgaris)* on the dry rim and cotton grass (*Eriophorum vaginatum)* and bell heather (*Erica tetralix)* in the depression. The bigger plateau dunes of up to about 5 ha are characterized by a buried soil profile, normally a podzol according to World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). The podzol B-horizon is rather impermeable because of enrichment with iron and aluminum and especially the formation of impermeable placic horizons; therefore, peaty layers up to about one and a half meters in thickness formed above the podzol. The peat layers are important for the formation of the plateau dunes because the surface of the peat is stable. It protects the plateau dune from deflation as occurred in its surroundings. Blow-out sand from the surroundings can accumulate on these wet peat surfaces. In the small plateau dunes, the peat layer is thin and often not > 20 cm thick; there is no rim or a central depression but the top has a convex shape with maximum aeolian sand deposited in the central part.

The plateau dunes are unique landforms described on the European Aeolian Sand Belt in the Netherlands, Germany and Denmark. They are present in Saale glaciation landscapes and on outwash plains from Weichsel (Koster, 2005; Koster, 2009; Tolksdorf and Kaiser, 2012). Previously, plateau dunes received relatively little attention in the

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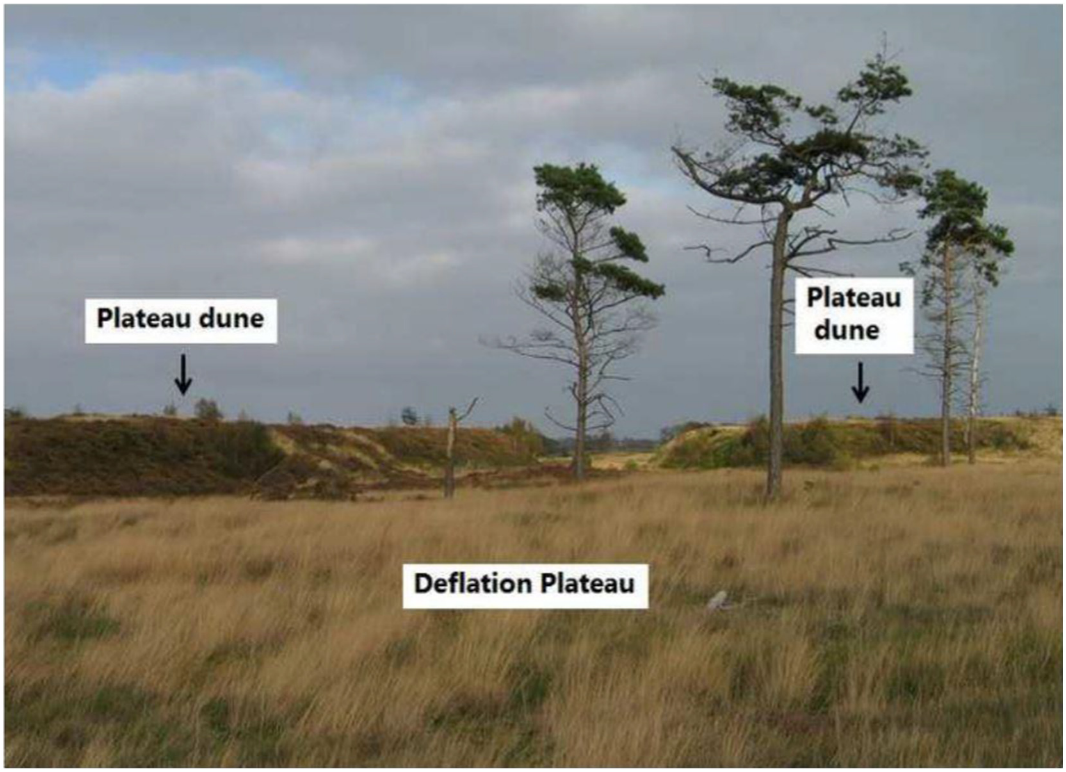

Fig. 1. A typical plateau dune from the Stensbæk research area.

scientific literature. In the Netherlands, Polak (1968), Koster (1970, 1978) and Castel (1991) investigated peat layers in plateau dunes in Veluwe and Drenthe. Through pollen and ^{14}C analyses, they found that the peat formation ended 700–900 years ago; the drift of sand taking place at some point thereafter. In Germany, Solger (1910) described plateau dunes, and Sørensen (1939, 1972), Hansen (1966), Stenz and Sørensen (1969) and Breuning-Madsen et al. (2013) described plateau dunes from Denmark. In the Frøslev Plantation, the age of the peat in a plateau dune was determined through ^{14}C analysis to be about 850 years old (Sørensen, 1972).

The dating of the plateau dunes was previously limited to ^{14}C dating of the peat layer in the dunes, and it was therefore impossible to date the different phases of development. The introduction of OSL dating enabled dating of the deposition of both aeolian and alluvial sand. It is now possible to date the complete development of the plateau dunes by combining AMS ^{14}C and OSL dating.

In this study, we show, based on studies of landscape morphology, soil profile development, chemical and physical soil analyses, and through dating using AMS ^{14}C and OSL methodologies, that the formation of a plateau dune landscape is due to a combined effect of pedology, land use and climate.

2. Study site

We investigated the plateau dune landscape in the Stensbæk Plantation in Southern Jutland, Denmark (Fig. 2). It is located on a narrow outwash plain between two Saale glaciation landscapes. For a short period after the Ice Age, the natural vegetation was birch and pine followed by several thousand years of deciduous forest (oak, lime ash and hazel). Beech became the dominant tree in Denmark about 2500 BP due to climate change, and in sandy areas, heather became common (Iversen, 1973). Over the past 6000 years, human activity has turned part of the land into farmland (Aaby, 1986). The study site has a humid temperate climate. The average temperature in the warmest month July is about 16 °C and in the coldest month January it is about 0 °C. The average yearly precipitation is app. 750 mm (DMI, 2017).

Fig. 3 shows a topographic map (LIDAR based digital elevation model) from the Danish Geodata Agency, (2015). The wind has blown away large volumes of sand and the surface level fell several meters forming a deflation plateau at about 14.5 m above sea level. On the plateau, > 10 well-developed plateau dunes exist (Fig. 3). The well-developed plateau dunes rise about 3–5 m above the blow-off or deflation area, and their top level is almost the same as that of the outwash plain towards the west. Today the vegetation is mainly heather, but in former times, forests and agriculture probably existed. East of the plateau dune area towards the river, a dune rim is seen (Fig. 3). Drift sand from in-between the plateau dunes have probably built up the rim.

3. Field work

All potential plateau dunes recognized on the elevation model (LIDAR) were verified in the field. The plateau dunes with steep slopes and a leveled top plateau were selected to perform auger drilling. The drilling was carried out using hand-driven chamber augers for sandy or stony soils, and the deepest borehole was about 4 m. In the central wet part of the plateau dunes, a casing was used below the groundwater level to prevent saturated sand from flowing into the borehole.

Based on the survey, two plateau dunes were selected to determine the formation of the plateau dunes in detail. One of the two plateau dunes studied was a three and a half meter high plateau dune through which a transect was excavated for a path construction (Fig. 3, letter A). This has partly drained the plateau dune and made it suitable for making a 2 m wide cut to the base (outwash plain) through its central part. The plateau dune was not the wettest of the plateau dunes, but even so it took some days before the water had stopped running into the cut. In this cut, it was possible to follow the outline of the placic horizons being the precondition for the development of peat layers (Sørensen, 1972). Furthermore, it was possible to make the OSL sampling by hammering 25 cm long metal tubes with a diameter of 2 cm into the profile wall. The OSL sampling strategy was to date the sandy

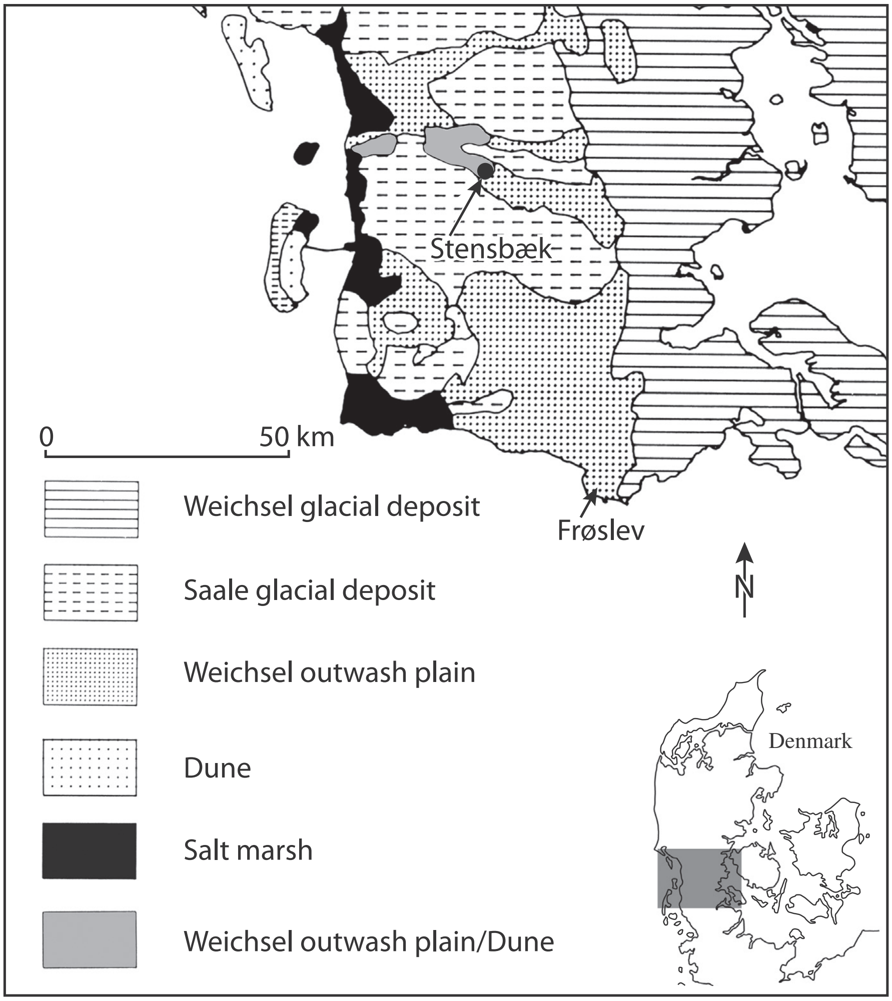

Fig. 2. Geomorphological map of Southern Denmark. The location of the Stensbæk research area is indicated by a dot.

deposits above and below the peat layer, but sampling for ^{14}C determination of the peat layer was omitted because it was a sapric peat with many fresh or partly decomposed roots. Samples were collected in distinct horizons for soil chemical and physical analyses in order to study the pedology of the sediments.

Peat samples for ^{14}C determination were collected from plateau dune B (Fig. 3 letter B) in order to study the formation of the peat layer especially according to time and vegetation history. The plateau dune B has 125 cm of peat below 150 cm of cover sand. The groundwater was very close to the surface and soil sampling was done by drilling using a chamber auger in the sand layer. Casing was used to stabilize the auger hole in the sandy layer. In the peat, drilling was performed using a half cylinder auger in order to obtain undisturbed samples. The major part of the peat was fibric and hemic peat that was very suitable for sampling plant remnants for ^{14}C dating. Well-defined plant remnants were also detected and sampled in the sapric peat.

Also in the sapric peat, well-defined plant remnants were detected and sampled. Furthermore, profile description and soil sampling were carried out from the rim and the central wetland to study the pedology.

4. Analyses

The soil samples from the various sites were air dried and passed through a 2-mm sieve. The texture was determined by the hydrometer method for silt and clay fractions and sieving for the sand fraction (Day, 1965). Total carbon content was determined by dry combustion at 1250 °C in oxygen (ELTRA, 1995). Soil pH was determined potentiometrically in a suspension of soil and 0.01 M $CaCl_2$ at a soil-liquid ratio of 1:2.5. The content of iron- and aluminum sesquioxides was determined by the dithionite-citrate-bicarbonate method (DCB) (Mehra and Jackson, 1960). Organic bound Al and Fe oxides were determined by pyrophosphate extraction as described by Schwertmann (1964).

4.1. ^{14}C determination

The age of the peat material was determined on 6 undecomposed plant remnants from one boring in plateau B (see Table 4) using ^{14}C dating by Accelerator Mass Spectrometry (AMS) at the AMS Laboratory at the University of Aarhus. The ^{14}C ages are reported in conventional radiocarbon years BP (before present = 1950) in accordance with international convention (Stuiver and Polach, 1977). Calibrated ages (Cal.BP) in calendar years have been obtained from the calibration curves in Reimer et al. (2009) by means of the Oxcal v4.1 calibration program (Ramsey, 2009) using the terrestrial calibration curve, IntCal09.

4.2. OSL determination

On return to the laboratory, the material from the outer 5 cm from each end of the tube was reserved for dose rate analysis; a portion of the inner material was reserved for water content measurement and another was used for luminescence measurements. The latter was wet-sieved to 180–250 μm and treated with HCl, H_2O_2 and concentrated HF

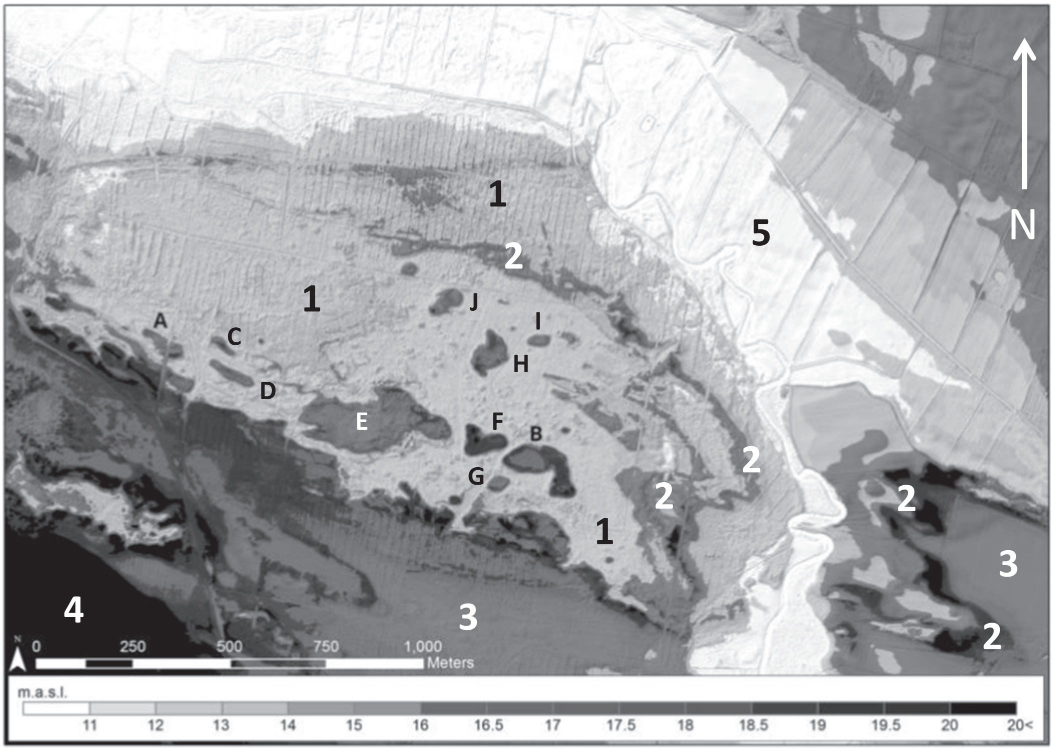

Fig. 3. The Stensbæk research area showing the plateau dunes as islands on the deflation plateau and the two plateau dunes investigated (A and B)
A–J: Plateau dunes
1: Deflation plateau
2: Parable dunes
3: Weichsel outwash plain
4: Saale glaciation landscape
5: Recent river valley.

in the usual manner to prepare a quartz extract (Wintle, 1997). Finally, the grains were mounted for later measurement on 9.8 mm diameter stainless steel discs using silicone oil.

Luminescence measurements were undertaken using a Risø TL/OSL reader model TLDA 20 incorporating a calibrated beta source of dose rate ~0.1 Gy·s^{-1}. Stimulation employed blue LEDs (470 ± 30 nm; ~80 mW cm^{-2} at the sample position) or infrared LEDs (870 ± 30 nm; ~150 mW·cm^{-2}). UV luminescence was detected through a U-340 glass filter using a photomultiplier tube.

Since quartz does not give a significant response to IR light, but only to blue, the luminescence purity of the quartz extracts was confirmed by comparing the effects of IR stimulation with those of the blue light stimulation (Duller, 2003).

The dose rate material from each end of the tube was dried and homogenized by grinding before mixing with wax (~60% sample) to retain radon gas and casting in a fixed cup-shaped geometry. These samples were then stored for > 20 days (five ^{222}Rn half-lives) before counting on a calibrated high resolution germanium detector to measure the activity concentrations of the uranium and thorium decay series, and ^{40}K (Murray et al., 1987). These concentrations were converted into dose rates using the factors given by Guérin et al. (2012), modified by the presumed lifetime water contents (Aitken, 1985) and added to the calculated cosmic ray dose rates (Prescott and Hutton, 1994). The doses in Table 1 are calculated as arithmetic means of 18–24 large aliquots per sample. Extreme outliers were omitted from the averages.

5. Results and discussion

5.1. The age and pedology of the sediments below and above the peat layer

Fig. 4 shows the stratification of plateau dune A based on a profile study for each 1 m along the cut, and Table 2 shows soil profile analytical data in the center of plateau dune A (Fig. 3). The level of the deflation area around the plateau dune is about 14.5 m above sea level. Close to the plateau dune, the deflation level rises gently up to about 17 m above sea level with a maximum height of 17.6 m asl. The top of the plateau dune outside the transect was a small dune rising to the height of 18.7 m asl. The west-facing rim is almost 17.0 m asl, while the central part and the eastern rim are 16.7 m asl and 17.5 m asl, respectively.

The top of the plateau dune consists of cover sand deposited about 330 years BP (Tables 2 and 4) during what is known as the Little Ice Age. The thickness of the layer varies between 25 cm in the central part of the plateau dune and about 1 m at the eastern rim. The fine sand is weakly podzolized with a light brownish grey E horizon upon a yellowish brown B horizon. The sandy layer is acidic with a low carbon content, gleyey or has pale hydromorphic colors and some mottles close to the peat layer below. In some cases, a weak or moderate placic horizon has developed (see Table 2) between the sandy layer and the peat below. The soils are arenosols at the rim and gleysols or histosols with a thin cover of sand in the central part of the plateau dune (according to IUSS Working Group WRB, 2006). There is a peat layer below the sand layer from the Little Ice Age. It is mostly a black or very dark brown extremely acidic blanket peat that can have > 50% carbon, see Table 2. The top level of the peat is at app. 16.65 m asl close to the edges and in the central part, it is app. 16.45 m asl and reaches its

Table 1
Multigrain and adjusted OSL ages from the two plateau dune investigated, A and B see Fig. 3. The errors show 1 standard error, n is the number of replicates and w.c. is the soil water content used for the age calculation.

Plateau dune	Horizon	Depth cm	Eq. Dose Gy	Number	Dose rate Gy ka^{-1}	w.c. %	Age 1000 years
A	C1	35	0.39 ± 0.01	24	1.18 ± 0.05	14	0.33 ± 0.02
A	AE	100	6.8 ± 0.3	18	0.70 ± 0.04	22	9.7 ± 0.7
A	2Cg	290	13.2 ± 0.5	24	1.11 ± 0.05	13	11.9 ± 0.8
A	3Cg	340	215 ± 1.1	21	1.21 ± 0.06	17	17.7 ± 1.3
B	C	70	0.33 ± 0.01	21	1.00 ± 0.04	18	0.33 ± 0.02
B	2C	App. 400	13.6 ± 0.4	21	1.28 ± 0.06	10	11.3 ± 0.6

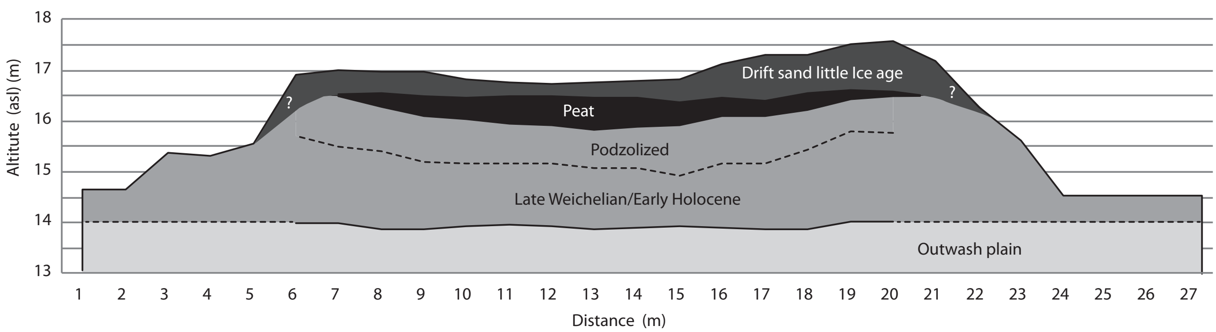

Fig. 4. Schematic transect through plateau dune A (see Fig. 3 for location). Late Weichselian/Early Holocene sand and sand from the Little Ice Age are aeolian deposits.

Table 2
Analytical data from the central part of plateau dune – for location see Fig. 3 OSL ages are before 2009.

Horizon	Depth	Texture**	Colour dominant	pH H_2O	Total C	CBD Fe	CBD Al	PyroP Fe	PyroP Al	Age OSL
	cm				%	‰	‰	‰	‰	1000 years
E	0–7	FS	10YR 6/2 dry	4.6	0.82	0.98	0.39	0.37	0.31	
Bws	7–18	FS	10YR 5/4 dry	4.4	0.60	1.04	0.71	0.40	0.51	
C1	18–39	FS	10YR 6/6 dry	5.0	0.38	0.96	0.92	0.20	0.71	0.33 ± 0.02
C2g	39–47	FS	2,5Y 4/6 moist	4.6	0.43	0.69	0.52	0.37	0.39	
2H	48–92	peat	7,5YR 2,5/1 wet	3.4	50.12	nd	nd	nd	nd	
2AEg	92–103	FS	7,5YR 2,5/2 moist*	4.3	2.98	0.21	0.89	0.04	0.79	9.7 ± 0.7
2Bhsg	103–113	FS	5YR 2,5/2 moist	4.2	3.36	0.23	2.17	0.02	1.93	
placic	113–114	FS	5YR 4/6 moist	4.8	2.21	41.12	2.05	11.90	2.10	
2Bs1g	114–148	FS	7,5YR 3/3 dry	4.5	0.41	0.96	1.95	0.48	1.49	
2Bs2g	148–170	FS	10YR 6/4 dry	4.6	0.08	0.64	0.80	0.16	0.63	
2Cg	170–240	FS	2,5Y 7/3 moist	4.6	0.02	0.74	0.72	0.14	0.71	
2Cg	240–315	FS	2,5Y 7/3 moist	5.2	0.04	0.85	0.74	0.18	0.60	11.9 ± 0.8
3C1	315–325	gCS	2,5Y 6/4 moist	5.1	0.02	1.33	0.81	0.26	0.77	
3C2	325–360	CS	2,5Y 6/4 moist	5.5	0.05	1.11	0.75	0.26	0.67	17.7 ± 1.3

*many white sand grains ** FS = fine sand, sand 63–200 mm and < 5% clay, CS = coarse sand; sand > 200 mm and < 5% clay g = gravelly.

maximum thickness of about 65 cm. The peat layer becomes thinner towards the edge and disappears close (about 5 m) to the slope towards the deflation area. The difference between the level of the deflation plain and the level of the peat at the edges is about 2 m (16.6 m asl–14.6 m asl) indicating a blow-off of 2 m of cover sand most likely during the Little Ice Age. Below the peat layer, a very strong podzol has developed in dune sand deposited about 10,000 years ago. It has a dark greyish E horizon followed by a black (humus) and a reddish brown (iron) spodic horizon. A typical horizon sequence is Eg, Bhg, placic, Bs, C or Eg, Bhg, Bsg, Placic, Bs, C. In some cases, several placic horizons have developed at various depths. For example, at one place five placic horizons were detected at the following depths in cm: 70, 137, 187, 195, 315. The podzol's *E*-Bh-Bs is about 1 m thick, very acidic and with high carbon content. The placic horizons impede the infiltration of the precipitation surplus during the year and a perched water table develops. This drains internally through the peat free edge without placic horizons and no water seeps from the base of the plateau dune. The strongly developed podzol is followed by app. 1 m of C horizon in acidic c sand low in carbon content before we find the 18,000 BP old coarse sandy outwash plain from the Weichsel glaciation. There is no soil development on the top of the outwash plain as this blew away during the aeolian activity in the Late Weichselian/Early Holocene era. The level of the outwash plain below the plateau dune is app. 13.8 m asl. The deflation plateau outside the plateau dune is app. at 14.6 m asl showing that the storms about 330 years ago did not blow away all the Late Weichselian/Early Holocene sand, and almost 1 m of this is still left behind.

The study of plateau dune A shows that aeolian activity in Late Weichselian/Early Holocene has reworked the top meters of the outwash plain. In the Late Weichselian/Early Holocene sand, a strong podzolization has taken place and placic horizons have made the soil B horizon impermeable and a peat layer has formed upon the mineral deposits. The peat layer in the central part of plateau dune A is only covered by a thin layer of sand and the peat is densely penetrated by roots from the vegetation above. Without podsolization and formation of placic horizons, the soil has remained well drained and no peat layers were formed protecting the surface for wind erosion. This shows that pedology is an important factor forming the plateau dunes. One

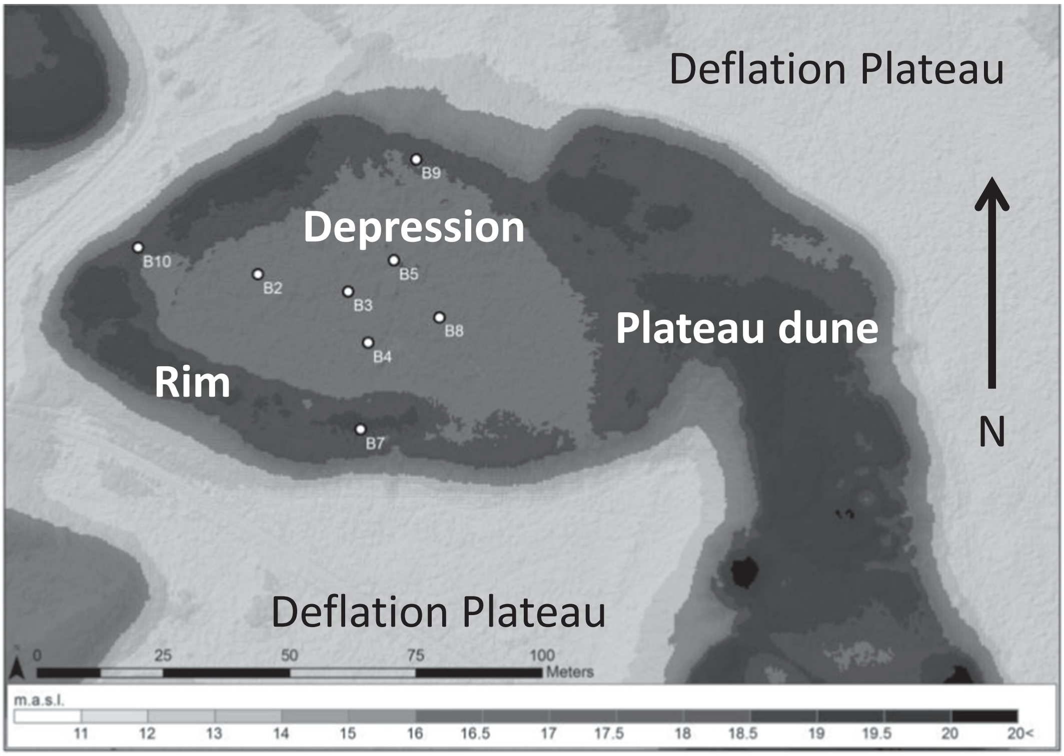

Fig. 5. Detailed map of Plateau dune B (see Fig. 3 for location) and the location of the drillings (see Table 2). All surface sands are aeolian deposits.

question to be answered is when did the podsolization occur in the Late Weichselian/Early Holocene sand forming the basis for the formation of the peat layer and thereby the plateau dune.

5.2. The peat layer in the plateau dunes

The peat layer in plateau dune A is mainly sapric and relatively thin, < 60 cm. It is not well-suited for studying the development of the peaty layers in the plateau dunes. Thus Plateau dune B (Figs.3 and 5) has been chosen for studying the peat development in the plateau dunes. It has a thick mainly fibric peat layer covered by a thick layer of aeolian sand preventing roots from penetrating the peat layer.

The deflation plateau around the plateau dune B is located at about 14.5 m asl (Table 3), almost similar to plateau dune A. A profile located on the deflation plateau close to the plateau dune B shows 90 cm Late Weichselian/Early Holocene sand covering the outwash plain sediment. The plateau dune has steep slopes and the rim is 4 to 4.5 m above the deflation plateau. The top of the plateau dune is concave and the central part is 0.6–1.0 m lower than the rim. A peat layer in the central part is covered by aeolian sand about 3–400 years old similar to plateau dune A. In this case, the aeolian sand cover is much thicker, approximately 1.5 m.

Table 3
The level of the plateau dune B, the top and bottom level of the peat and the thickness of the peat layer from 8 drilling; three close to the rim and five in the central depression. The sites are shown on Fig. 5.

Site	Top level plateau dune meter	Top level peat meter	Bottom level peat meter	Thickness peat meter
Plain east	14.52	–	–	–
Plain west	14.50	–	–	–
average	14.51			
Close to Rim				
B10	18.52	17.82	17.53	0.29
B9	18.66	17.60	17.15	0.45
B7	18.93	17.31	–	–
average	18.70	17.58	17.34	0.37
Central part				
B2	18.13	16.93	15.80	1.14
B3	18.10	16.45	15.31	1.14
B4	18.01	16.59	15.34	1.25
B5	18.15	16.62	15.46	1.16
B8	18.15	16.69	15.61	1.08
average	18.11	16.66	15.50	1.15

The thickness of the sand layer and the shallow perched groundwater throughout the year result in low root penetration to the peat layer below where mainly fibric or hemic peat is found; in the lower part, some sapric peat was noted but it was still possible to find useful plant remnants for ^{14}C determination. The maximum thickness of the peat layer was 1.25 cm in the central part of the plateau dune and from that site, soil samples were collected. The peat layer thins towards the edge and below the rim it disappears. The buried bog is drained internally through the rim and no water seeps out of the plateau dune at the base. A strongly well-developed podzol in Late Weichselian/Early Holocene sand appeared below the peat layer.

Table 4 shows that the peat formation began about 2600 years ago in the transition zone between the warm Bronze Age and the colder and wetter Iron Age. The cold and wet Iron Age climate favors formation of podzols and acid blanket peat, two of the essential factors for the later formation of plateau dunes. The formation of the peat in the bog continuously increases with rates from about 0.3 to > 2 mm per year. The decrease in the rate between the uppermost peat horizon and the horizon below might partly be due to compaction as 1.5 m of drift sand has been deposited upon the peat layer. The growth of the peat layer stopped about 400 years ago during the Little Ice Age, when huge storms blew away 3 m or more of the Late Weichselian/Early Holocene sediments and buried the peat below an aeolian sand cover, which in some cases is up to 1.5 m thick. The study of plateau B shows that the strong podsolization and formation of impermeable placic horizons took place about 2500 years ago when the climate became wetter and colder at the border between the Bronze Age and the Iron Age.

Table 4
Dates from the central part of plateau dune B. Calibrated ^{14}C ages are based on a 95% of the probability distribution and are given in cal.BP (years before 1950). OSL ages are before 2009.

Depth in peat layer (cm)	Depth from surface (cm)	C14 age years BP	Age in calendar years	Accumulation rate (mm/year)	Material	Dating method
–	150		330 ± 20		aeolian sand	OSL
5	155	583 ± 35	652–531	1.41	peat	^{14}C
25	175	832 ± 35	796–672	2.65	peat	^{14}C
60	210	976 ± 35	938–794	0.39	peat	^{14}C
85	235	1.636 ± 35	1,613–1,414	0.35	peat	^{14}C
110	260	2.196 ± 35	2,326–2,126	0.28	peat	^{14}C
125	275	2.624 ± 30	2,785–2,721		peat	^{14}C
–			11,270 ± 630		aeolian sand	OSL

Table 5
The soil at the rim and in the central part of the plateau dune B.

Horizon	Depth	Texture**	Colour dominant	pH H_2O	Total C	CBD Fe	CBD Al	Pyroph Fe	Pyroph Al
	cm				%	‰	‰	‰	‰
The rim									
O	5–0	mor	10YR 2/2 moist	3.8	22.9	1.91	0.87	–	–
AE	0–5	FS	10YR 3/1 moist	4.3	1.9	1.27	0.46	0.53	0.19
Bhs	5–16	FS	7,5YR 2,5/3 moist	4.5	0.7	1.67	0.64	0.84	0.55
Bs	16–25	FS	10YR 4/6 moist	4.9	0.3	1.24	0.99	0.51	0.91
C	25–110	FS	10YR 5/6 moist	5.5	0.1	1.10	0.81		
Cg	110–	FS	10YR 4/2 wet	–	–	–			
Depression									
H	0–8	peat	10YR 2/1 wet	3.8	36.0	–	–	–	–
Ag	8–14	FS	10YR 3/2 wet	4.3	1.4	0.25	0.46	–	–
Bg	14–22	FS	10YR 3/4 wet	4.6	0.6	0.56	0.81	–	–
Cg	22– >	FS	10YR 3/1 wet	5.2	0.3	0.54	1.05	–	–

5.3. The pedology of the cover sand on the plateau dunes

The soils have developed in a sandy parent material that was deposited 300–400 years ago. Table 5 shows data from a profile at the rim and from the central part of the plateau dune, see profiles in supplementary. The soil on the rim is very acidic, and the pH increases with increasing depths. The profile is a well-drained shallow podzol with hydromorphic features from the depth of 110 cm. At the top, it has a 5 cm very dark brown moor layer, and below that, a 5 cm thick AE horizon low in organic matter and with bleached sand grains present. Below, a thin, not cemented very dark brown Bhs and a dark yellowish brown Bs are detected. From the depth of 25 cm, a yellowish brown C horizon begins, from the depth of 110 cm, it shows hydromorphic features. There is no sign of thin surface layers (A horizons) or bioturbation in the C horizon of these aeolian deposits. This means that the sand was probably deposited within a very short period about 330 years ago, maybe during one big storm, because it must have taken some 100 years to develop the podzol in the rim. Compared to the podzols developed in Late Weichselian/Early Holocene sand, the podzolization process on the rim is very weak. This might be explained by a young age, as the sediment was deposited only 300–400 years ago.

The soil type in the central part is gleysols with a groundwater level about 30 cm in summer and temporary free water tables during winter due to precipitation surplus. The topsoil is an 8 cm thick very acidic peat (organic carbon content of 36%) followed by a 6 cm thick acid A horizon, an 8 cm thick Bg and from the depth of 22 cm, we have the C-horizon. All horizons show hydromorphic features.

6. Plateau dunes outside Denmark

Outside Denmark, plateau dunes are well known in the Netherlands. Koster (1978) studied the formation of table-shaped drift sand mounds (“forts”) in Northern Veluwe, and Castel (1991) studied Late Holocene aeolian drift sands in Drenthe (The Netherlands). The top of the peat layer in the plateau dunes in Drenthe was dated by the ^{14}C method and differed geographically, but no OSL dating of the drift sand on top of the peat was carried out. Based on the ^{14}C dating, the drift sand deposition on top of the peat layers started after year 1200 CE in the south western part of Drenthe, and before 1700 CE, all peat areas on the plateau dunes were probably covered with sands. A sequence of drift sand deposition occurred from west to east, probably due to a combination of increasing population pressure (deforestation) and physical circumstances (climate change). Thus, the formation of the cover sands over the peat and the formation of the plateau dunes occurred in the Little Ice Age, both in Denmark and the Netherlands.

7. Conceptual model on the development of the plateau dune landscape

The history of the formation of plateau dunes in the Stensbæk area is based on field observations, chemical and physical analyses of the soils and sediments, OSL dating of the mineral soil layers and by ^{14}C dating of the blanket peat.

1. An outwash plain was formed in the last part of the Ice Age from about 18,000 years BP, while the ice was stagnant at the main stationary line in mid-Jutland. The sediment was well sorted, coarse sand or gravel according to the meltwater discharge.
2. During the next 6000 years until about 11,000 years ago, tundra vegetation must have been established and some soil formation must have taken place. In the Late Weichselian and in the Early Holocene, wind activity reworked the top 4 to 5 m of the meltwater deposits turning it in to aeolian sediments.
3. In the Holocene, the surface of the outwash plains remained fairly stable for several thousand years. Land clearing for cultivation or major fires resulted in landscape degradation and subsequent wind erosion. The vegetation was mainly scrub or oak and hazel forests (Aaby, 1986) and the sandy soils were probably only weakly podzolized if present.
4. The climate became colder and wetter at the transition between the

Bronze Age and the Iron Age (van Geel et al., 1996; Groenman-van Waateringe and van Geel, 2017). Beach forest and heathers (caluna vulgaris) became common (Aaby, 1986) and the heathers were used in the agricultural system for grazing and bedding in the stalls and then as manure.

5. The sandy soils podzolized, and spodic horizons with thin placic horizons developed, probably most frequently in the gentle depressions on the outwash plain. Parts of these became impermeable to water, and nutrient-poor bog or blanket peat developed.
6. A subsequent cultivation of the land between the bogs opened up the landscape, and wind erosion from the fields took place. Aaby (1986) showed from pollen analyses in the Abkær bog east of the plateau dunes that the landscape during the Little Ice Age opened up, especially in the cold periods from year 1250–1450 and after 1550 where heather vegetation dominated.
7. Based on the OSL dating of the drifting sand on top of plateau dune A and the ^{14}C dating of the peat layer from plateau dune B, the final design of the plateau dune landscape must have taken place in the second cold period about 400 years ago. The deflation areas between the moorland sank about 2 to 3 m, so that the top of the plateau dunes today is up to more than four meters above the current base surface.
8. A huge amount of sand was blowing from the west towards east. Some of the sand has probably blown into the river valley making it rather narrow, see Fig. 3, and some has built up the parable dune just west of the river valley. The dunes were deposited within short time (year-decade) because no humus layer or bioturbation of the stratified sediment was detected in these deposits.
9. The well-developed plateau dune surfaces have a rim along the fringes and a depression in the middle, see Fig. 5. Peat covered the Late Weichselian/Early Holocene aeolian sands in patches in the early stage of the formation of the plateau dunes (Fig. 3). Thereafter, the wet peat trapped a thin layer of aeolian sand. The peat layer is thickest in central part of the patches and subsequently subsides more than the rim by compression of the peat due to the weight of the sand deposited.
10. Since the Little Ice Age, the sand on the rim has podzolized but due to its young age, it is still not as strong as it has occurred in the Late Weichselian/Early Holocene sand below the peat layers. The sand deposited at the rim was uniform and the dune systems did not have thin humus layer indicating that the sediment was deposited within a short time. In the central wet part, gleysols are most common; some with a thin sphagnum peat layer on top. In the small plateau dunes, the depression in the middle has not developed and weak podzolization dominates all over.

8. Conclusion

Plateau dunes are erosion relicts on the European Aeolian Sand Belt formed by interaction between pedology, climate change and human activity (vegetation). Due to pedological processes, impermeable iron pans (placic or spodic horizons) are formed. This leads to wet condition and formation of peatland in minor depressions. The peatlands protect the biotopes from wind erosion. Climate change (the little Ice Age) and human activity removing the plant cover result in severe wind erosion between the peatlands forming the plateau dunes as erosion relicts or the negative forms compared to normal dunes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2018.07.011.

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